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**Damodaran et al.**

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(54) **PROGRAMMABLE BUILT IN SELF TEST OF MEMORY**

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**GIIC 29/00** (2006.01)  
**GIIC 7/00** (2006.01)

(52) **U.S. Cl.** ..... **714/718; 365/201**

(58) **Field of Classification Search** ..... **714/718**  
See application file for complete search history.

(56) **References Cited**

#### U.S. PATENT DOCUMENTS

4,313,200 A \* 1/1982 Nishiura ..... 714/736

5,157,664 A \* 10/1992 Waite ..... 714/710  
5,640,509 A \* 6/1997 Balmer et al. .... 714/42  
6,321,320 B1 \* 11/2001 Fleischman et al. .... 711/217  
6,560,740 B1 \* 5/2003 Zuraski et al. .... 714/733  
6,622,269 B1 \* 9/2003 Ngo et al. .... 714/718  
6,769,081 B1 \* 7/2004 Parulkar ..... 714/733  
2002/0108073 A1 \* 8/2002 Hughes ..... 714/7  
2002/0194545 A1 \* 12/2002 Abbott ..... 714/42  
2003/0084389 A1 \* 5/2003 Kottapalli et al. .... 714/733  
2004/0025095 A1 \* 2/2004 Nemani et al. .... 714/710  
2004/0103355 A1 \* 5/2004 Correale et al. .... 714/733  
2005/0047229 A1 \* 3/2005 Nadeau-Dostie et al. ... 365/201

\* cited by examiner

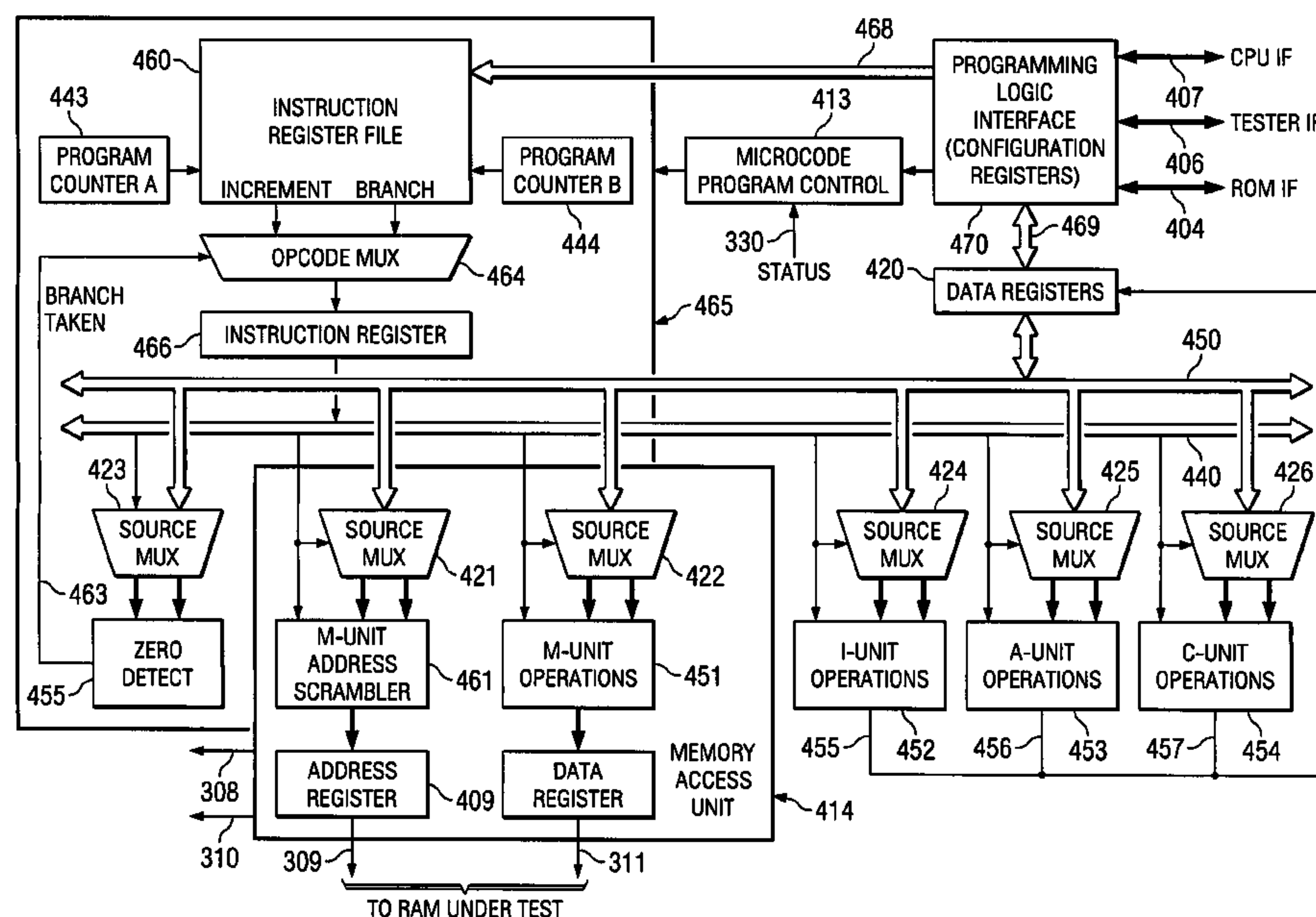
*Primary Examiner*—Cynthia Britt

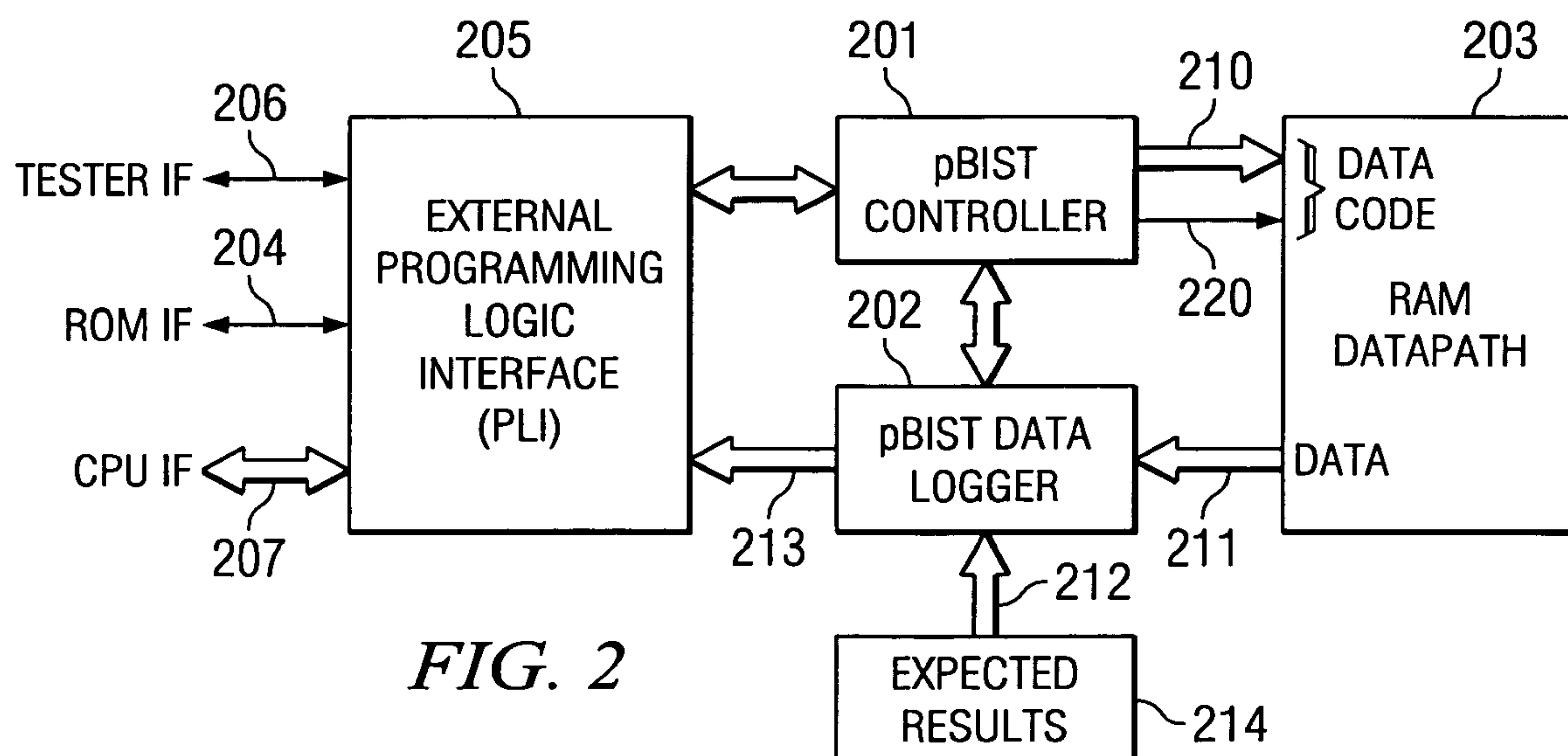
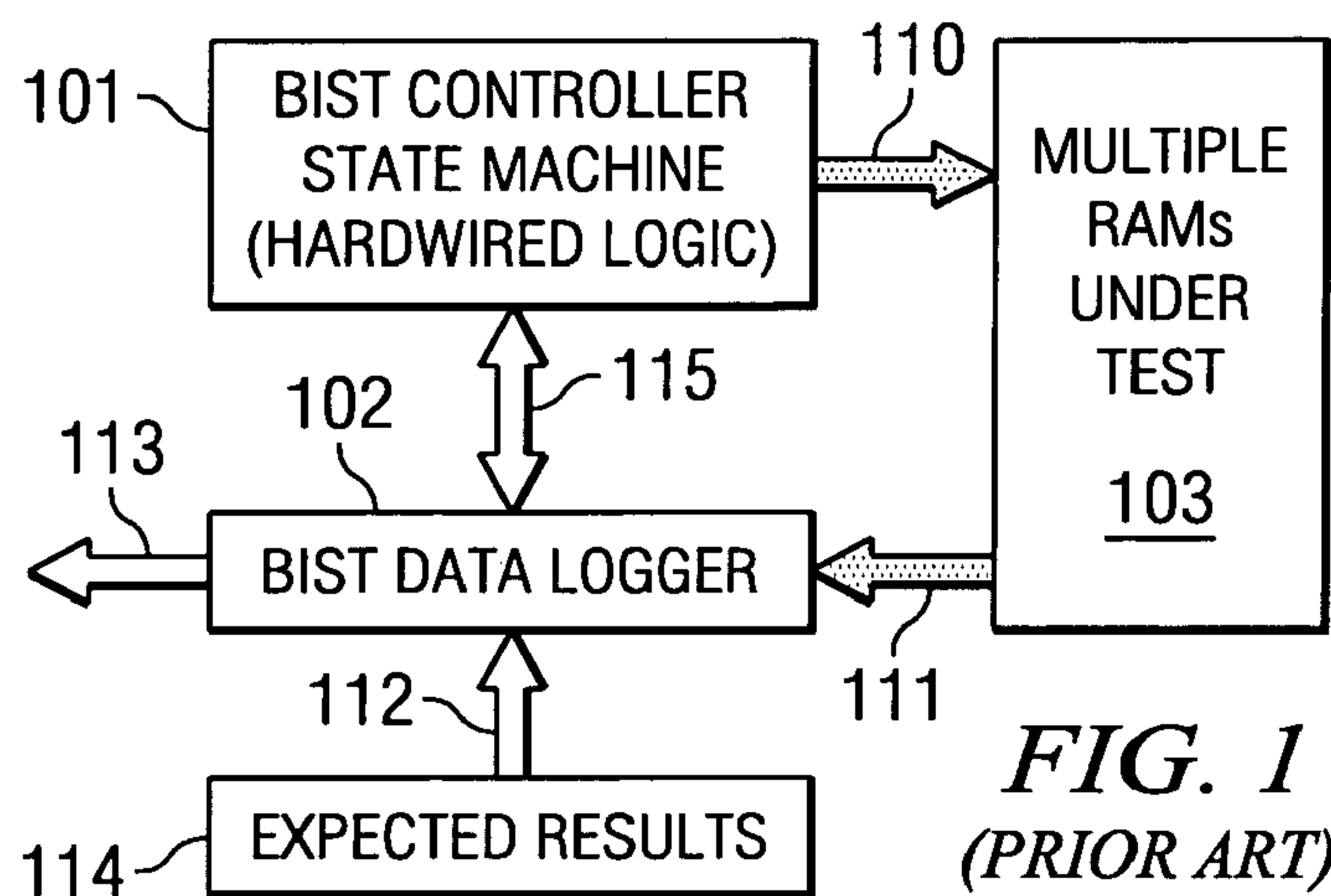
(74) *Attorney, Agent, or Firm*—Robert D. Marshall, Jr.; W. James Brady; Frederick J. Telecky, Jr.

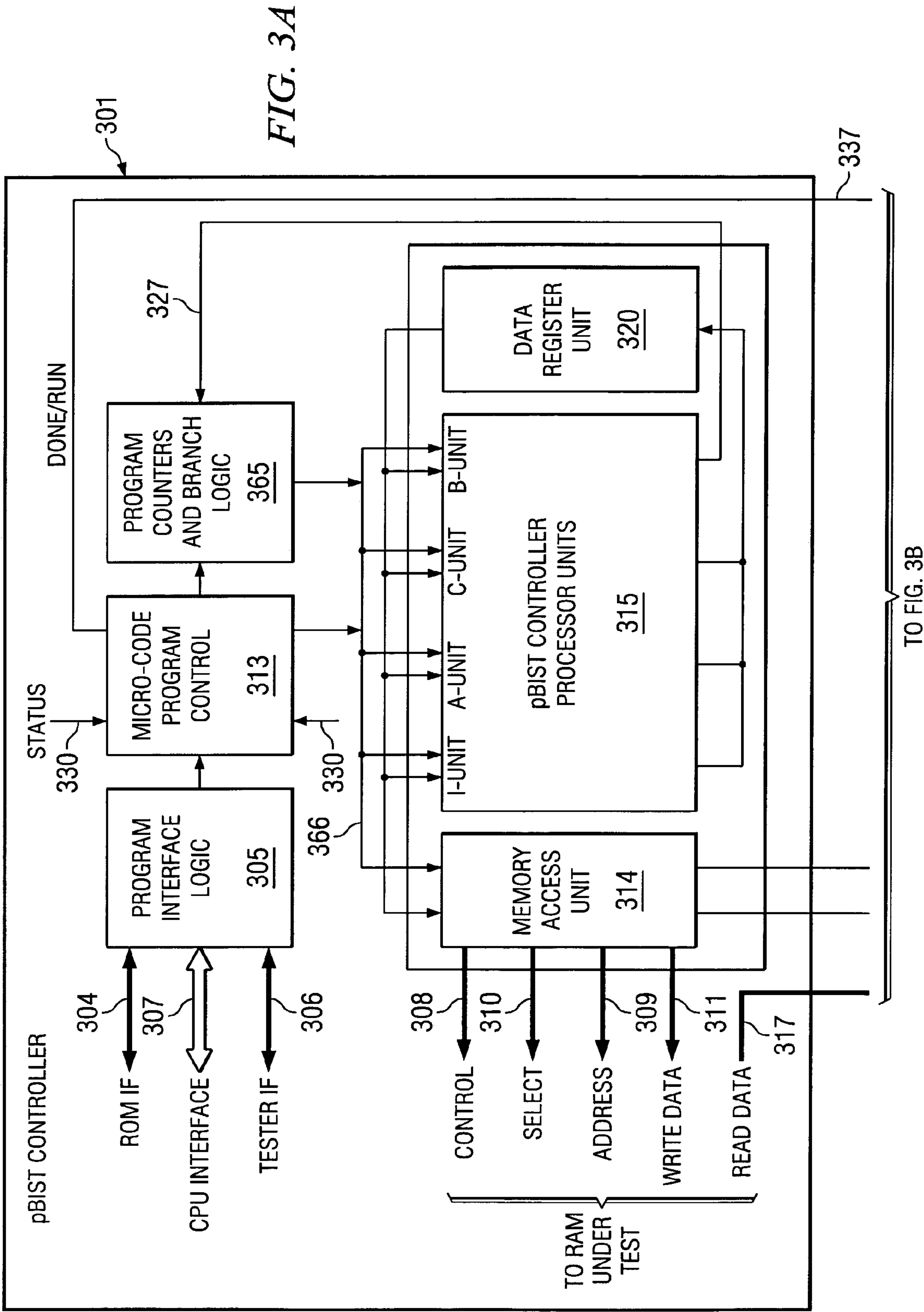
(57) **ABSTRACT**

The pBIST solution to memory testing is a balanced hardware-software oriented solution. pBIST hardware provides access to all memories and other such logic (e.g. register files) in pipelined logic allowing back-to-back accesses. The approach then gives the user access to this logic through CPU-like logic in which the programmer can code any algorithm to target any memory testing technique required. Because hardware inside the chip is used at-speed, the full device speed capabilities are available. CPU-like hardware can be programmed and algorithms can be developed and executed after tape-out and while testing on devices in chip form is in process.

**5 Claims, 10 Drawing Sheets**







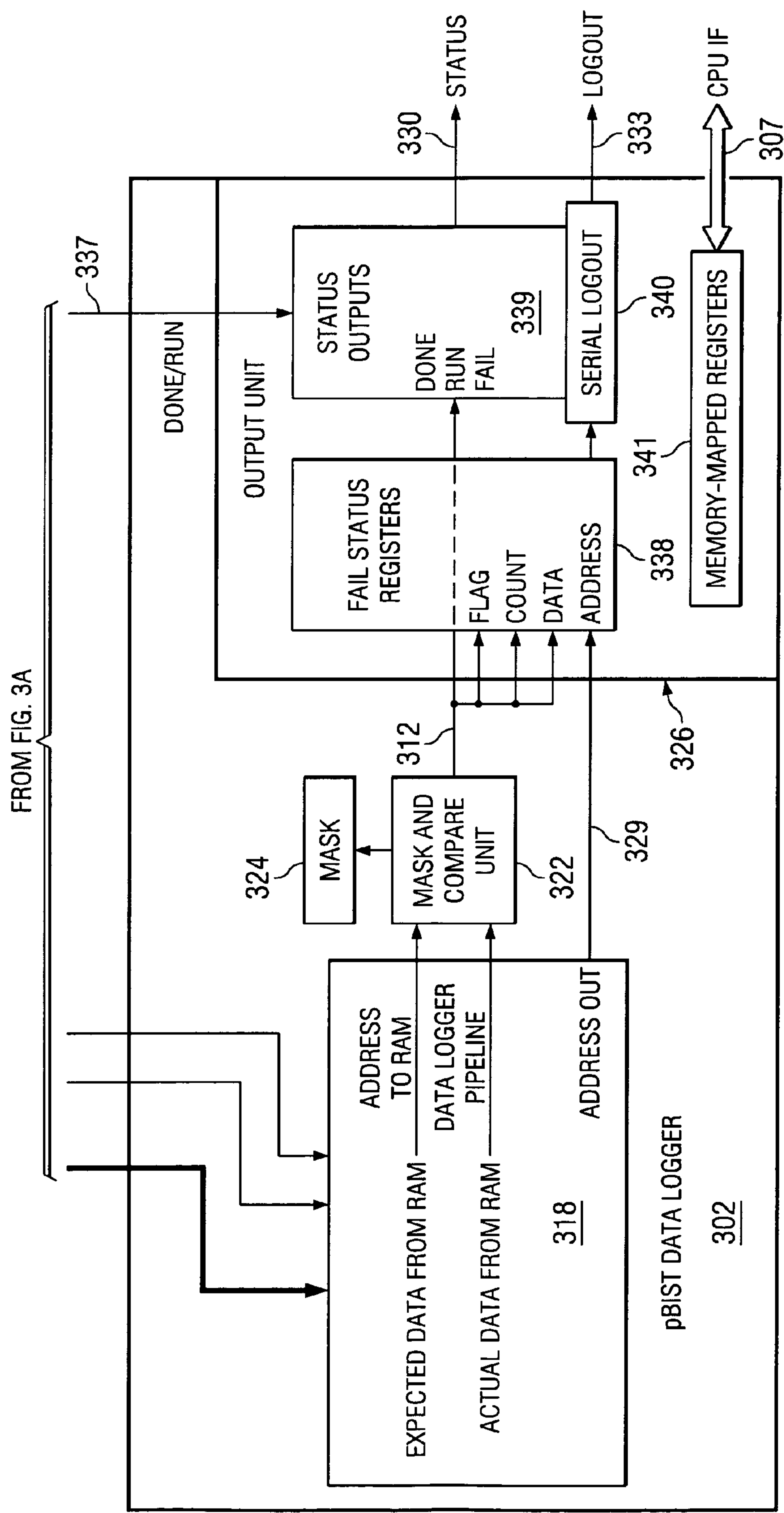


FIG. 3B



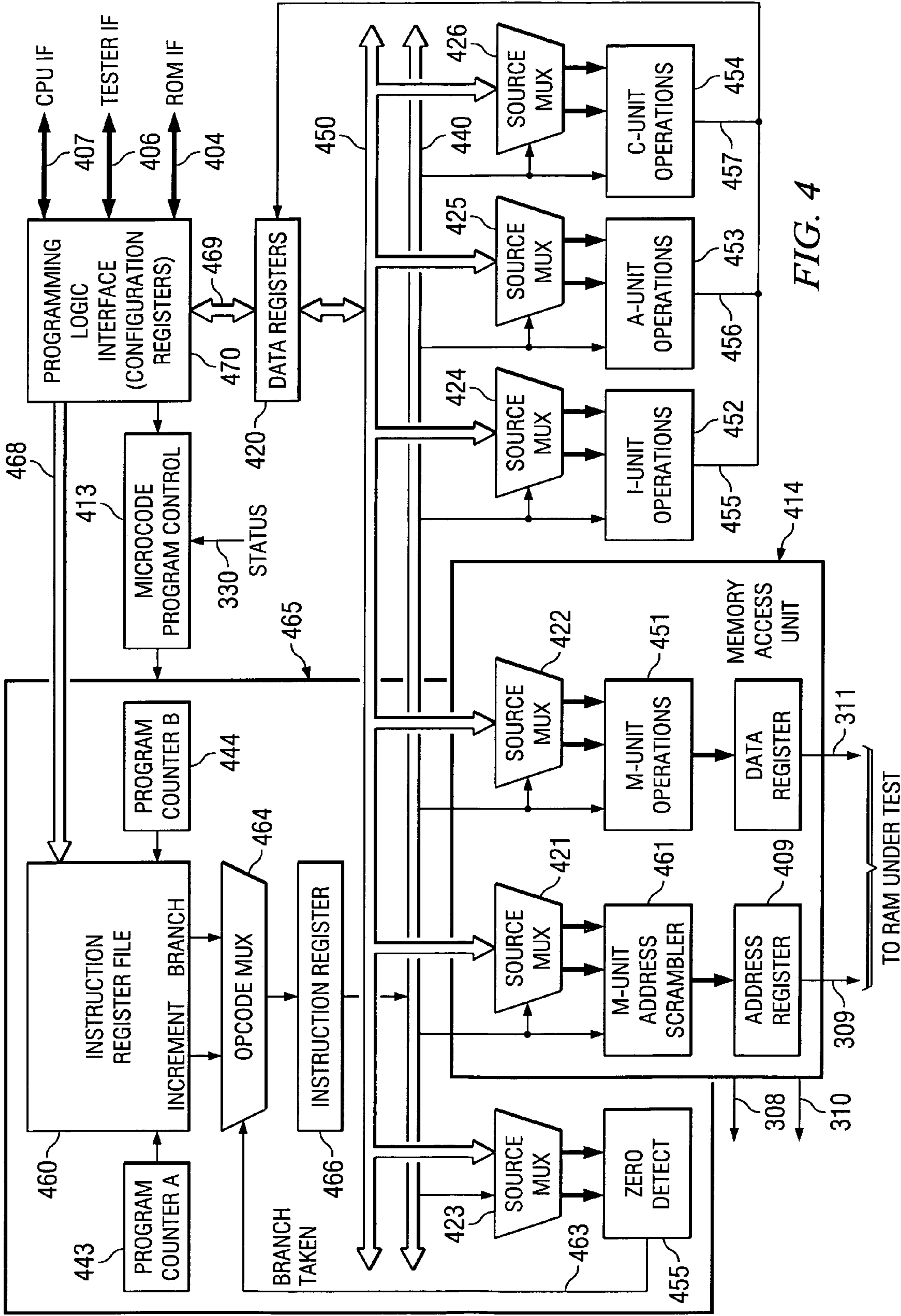


FIG. 4

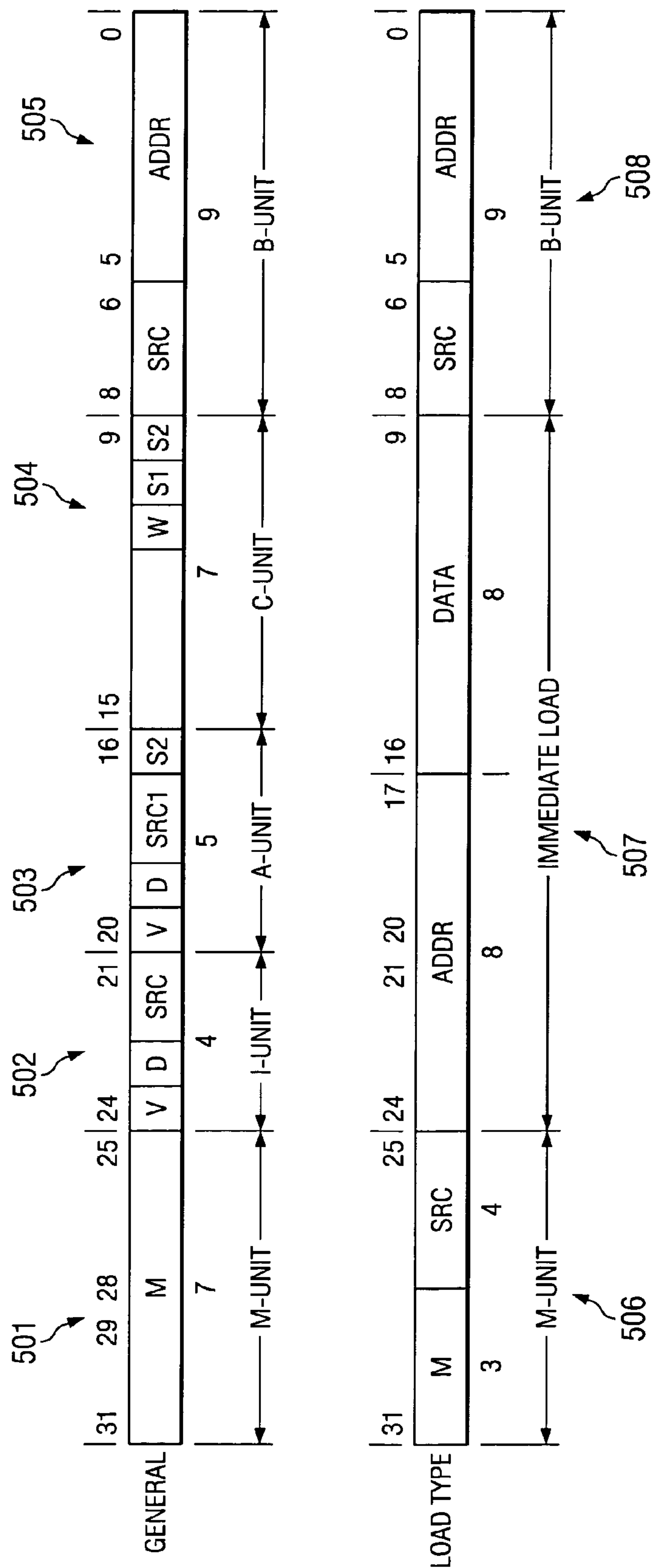


FIG. 5

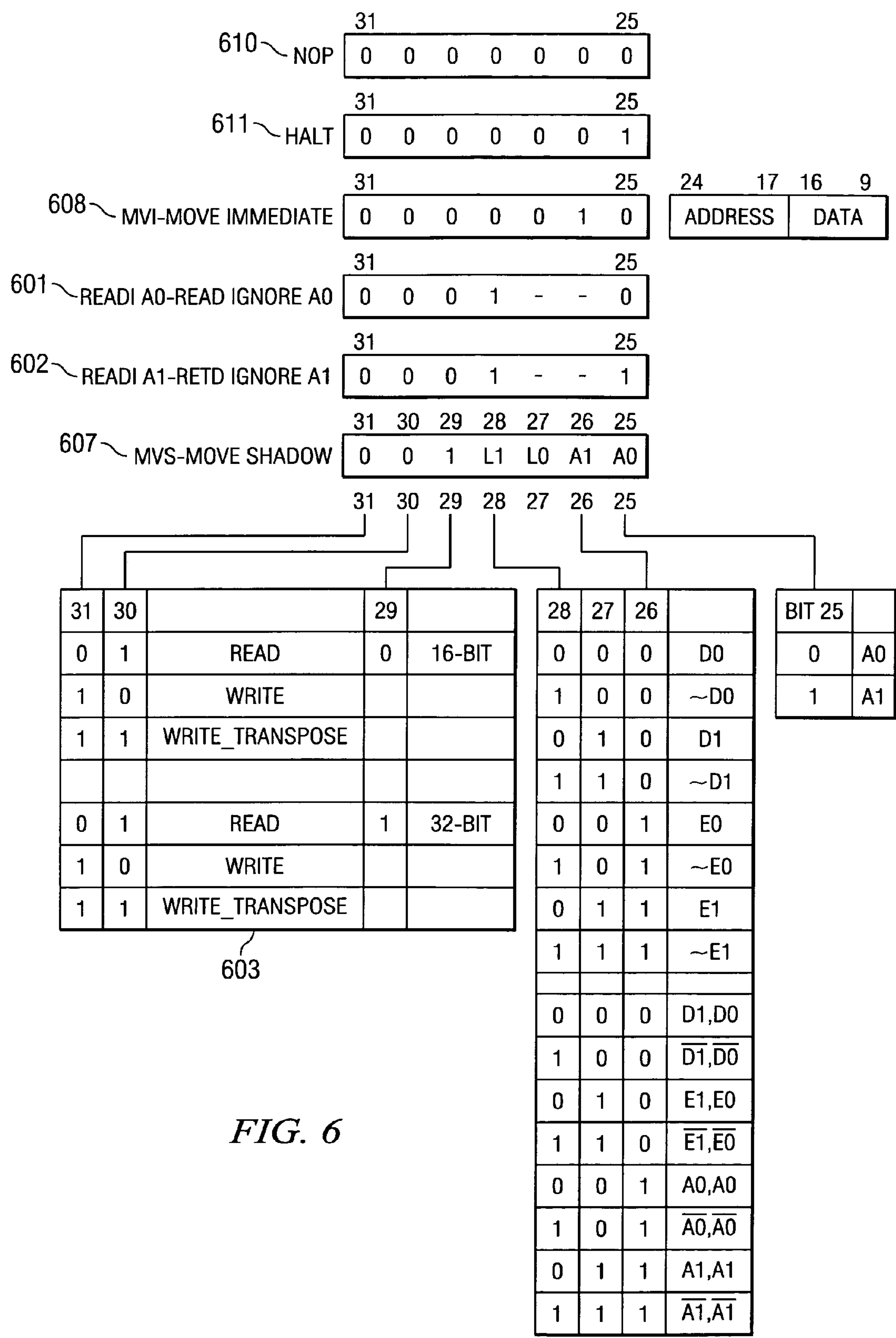


FIG. 6

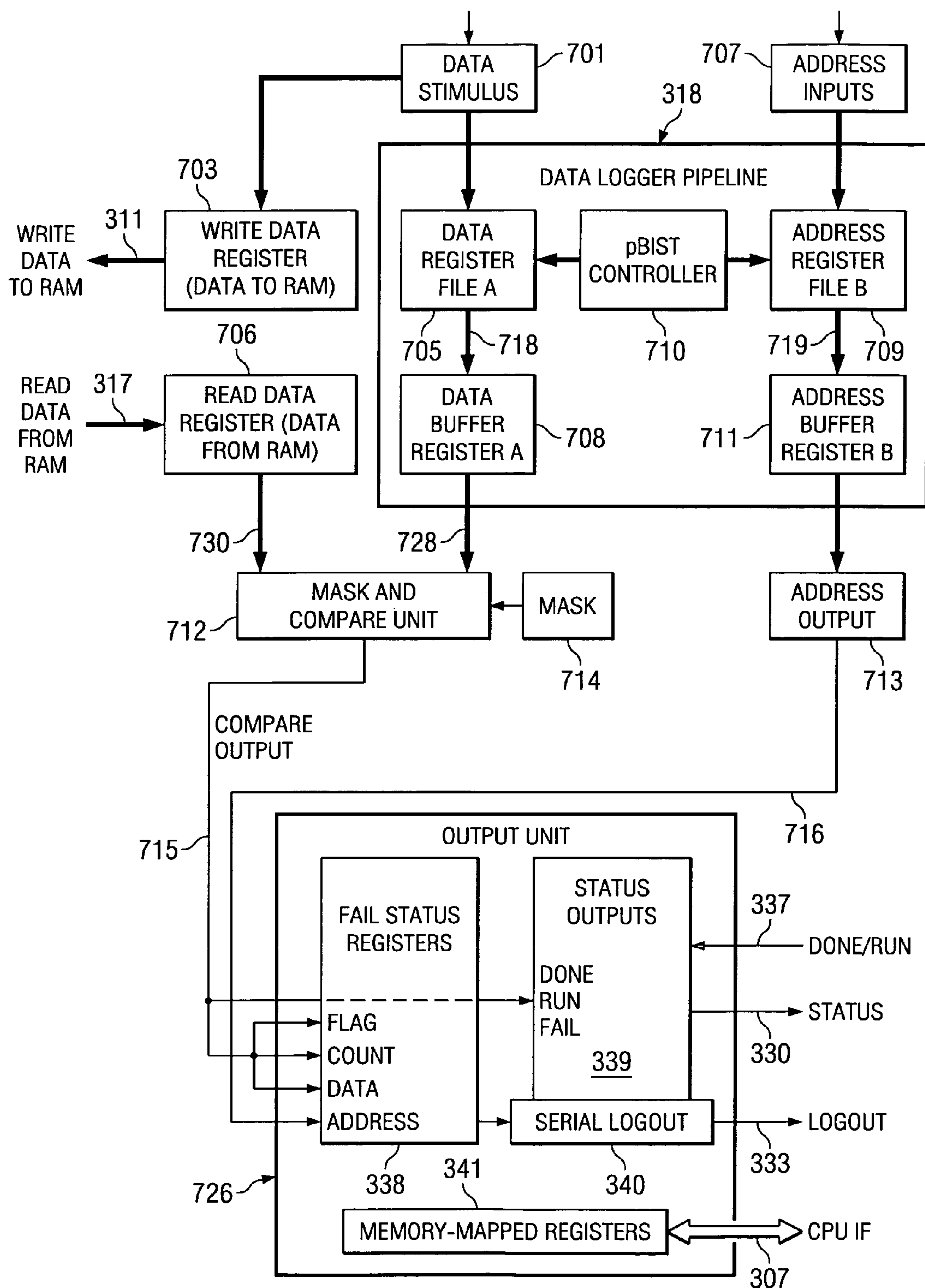


FIG. 7



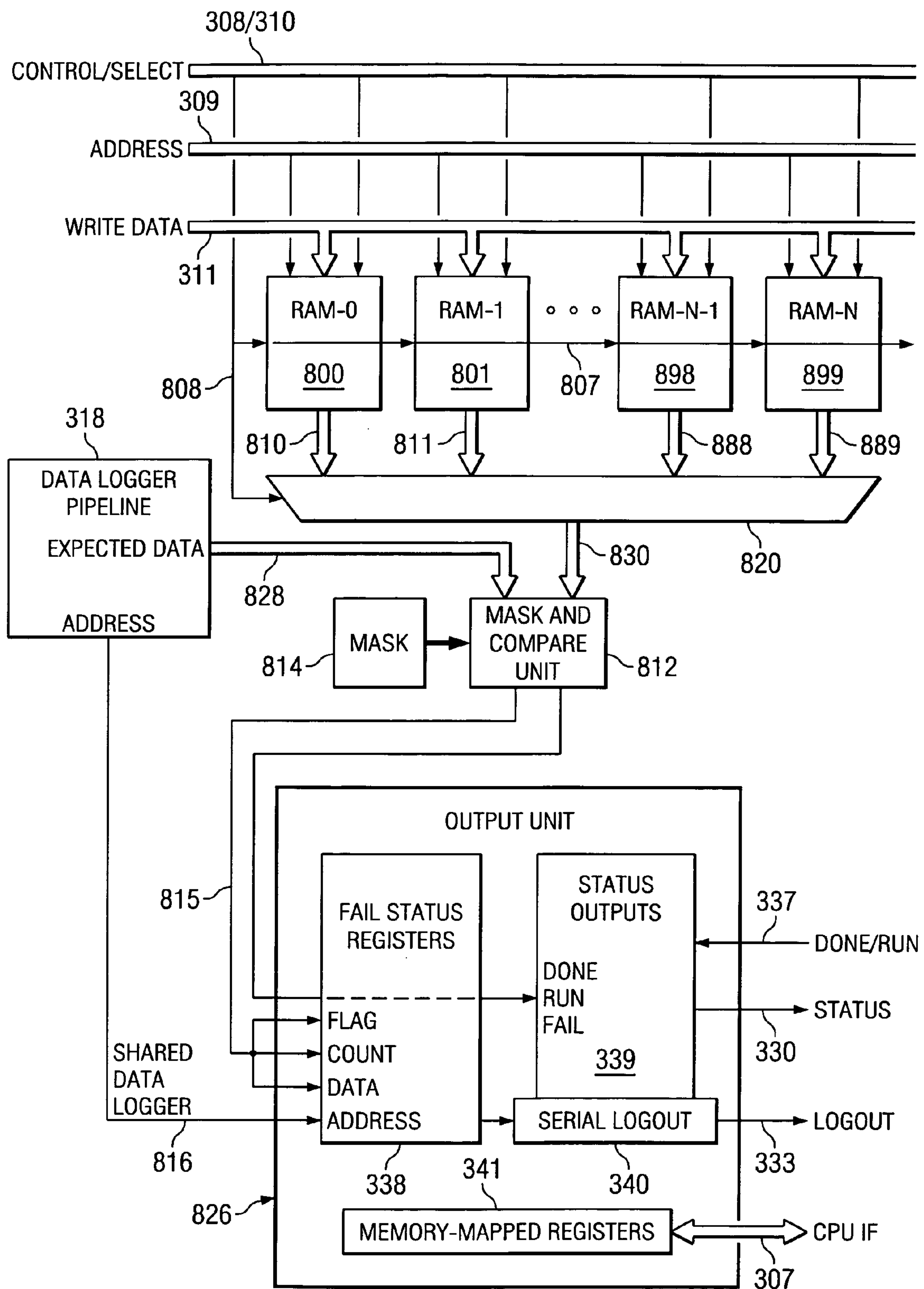


FIG. 8

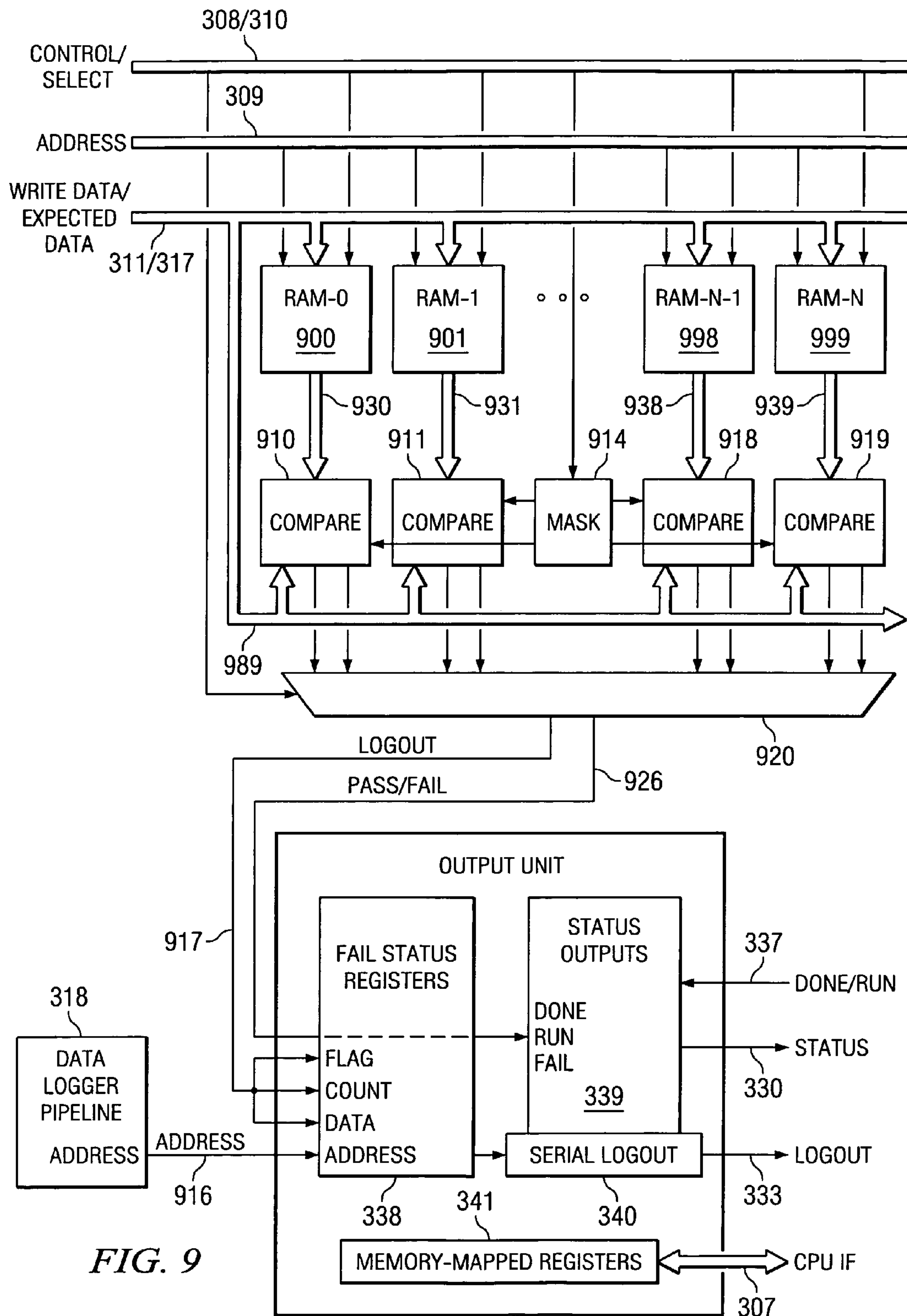
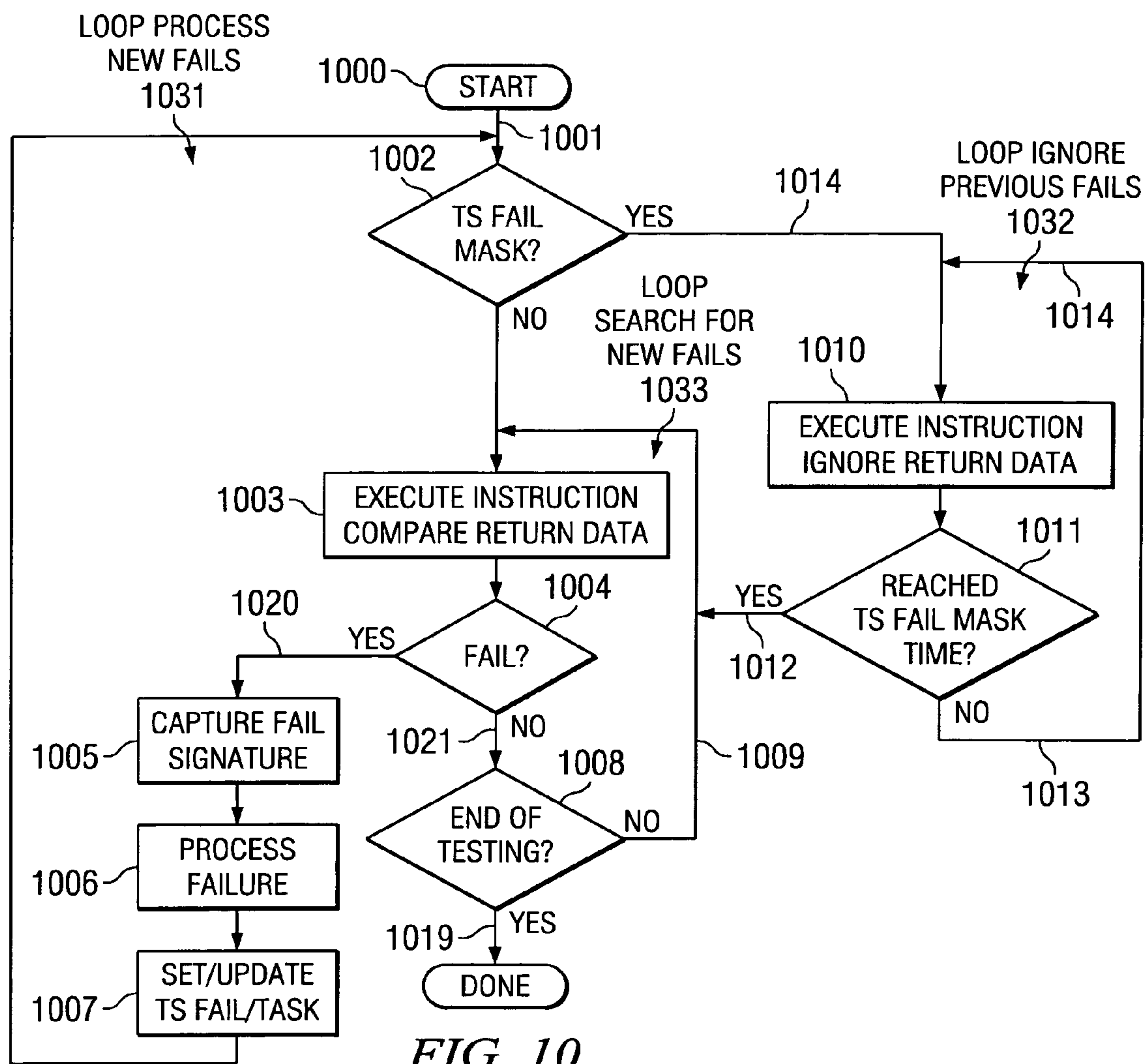


FIG. 9





## 1

**PROGRAMMABLE BUILT IN SELF TEST OF  
MEMORY**

This application claims priority under 35 USC §119(e)(1) of Provisional Application No. 60/527,310 (TI-36126PS), filed Dec. 5, 2003.

**TECHNICAL FIELD OF THE INVENTION**

The technical field of this invention is manufacture memory testing.

**BACKGROUND OF THE INVENTION**

In conventional VLSI systems memory testing is done in three essential steps. In the first step, hardwired logic employs algorithms developed before the device is committed to tape-out. These are often available through third-party vendors, examples are memBIST, MSIST. Deciding on the detailed make-up of hardwired logic is not feasible because it is impossible to predict the necessary information derived from process model during the process qualification window. In the second step, conventional memory testing attempts to close testing gaps using central processing unit (CPU) based approaches. These have a number of limitations. The major limitation is that there may be memory functions largely inaccessible via a CPU interface. Another severe limitation is the inability to do back-to-back accesses to all memories. The third step uses DMA external memory accesses while the device is in wafer form. Such DMA external memory accesses cannot be accomplished at full processor speed. Thus a significant number of failures are not observable.

FIG. 1 illustrates a conventional memory built-in-self-test (BIST) block diagram. The core functions are: (1) the BIST controller state machine **101** made up of hard-wired logic; and (2) the BIST data logger **102**. The BIST controller **101** communicates with the BIST data logger **102** via bus **115** and supplies stimulus to multiple RAMs under test **103** via multiple buses **110**. BIST data logger **102** accumulates the test results via multiple buses **111** and passes them to an external interface via bus **113**. BIST data logger **102** compares expected results **114** received via bus **112** with return read data from the multiple RAMs **103** received via bus **111**.

Major difficulties with conventional BIST memory test systems include:

1. Test algorithms must be hard wired into the BIST controller state machine **101**;
2. Multiple RAMS must be driven with stimulus and results must be extracted from these multiple RAMs requiring complex interconnect paths;
3. Back-to-back memory access to all memories are not feasible; and
4. Memories cannot be tested at speed while in wafer form.

These and other problems with the prior art provide a need for a new kind of memory testing.

**SUMMARY OF THE INVENTION**

The pBIST (programmable built-in-self-test) memory testing of this invention is a combined hardware and software solution. pBIST hardware provides access to all memories and other such logic such as register files in pipelined logic allowing back-to-back accesses. The pBIST technique gives the user access to this logic through CPU-like logic. The user can program the pBIST hardware to employ any

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algorithm to target any memory in any memory testing technique required. Because hardware inside the chip is used at-speed, the full device speed capabilities are available. CPU-like hardware can be programmed and algorithms can be developed and executed after tape-out and while testing on devices in chip form.

**BRIEF DESCRIPTION OF THE DRAWINGS**

These and other aspects of this invention are illustrated in the drawings, in which:

FIG. 1 illustrates conventional BIST architecture for memory testing (Prior Art);

FIG. 2 illustrates the pBIST architecture block diagram;

FIGS. 3A and 3B together illustrate the interconnection diagram of the pBIST controller, pBIST data logger and interface;

FIG. 4 illustrates a lower level diagram of the pBIST microcontroller hardware;

FIG. 5 illustrates the pBIST instruction types and opcode fields for general and load type instructions;

FIG. 6 illustrates the opcode details for the M-unit;

FIG. 7 illustrates the basic data logger structure;

FIG. 8 illustrates the shared data logger structure;

FIG. 9 illustrates the distributed data logger structure; and

FIG. 10 illustrates the time stamp mode program flow chart.

**DETAILED DESCRIPTION OF PREFERRED  
EMBODIMENTS**

Programmable Built-In Self Test (pBIST) performs memory self test using a coherent hardware-to-software interface allowing hardware access to testing logic at-speed with software controlling the detailed manner of testing. Devices employing conventional testing techniques such as memBIST and MBIST are committed to hardware solutions without programmable capabilities for modifying algorithms that are found inefficient after tape-out. All revisions of the chip must have a corrected test algorithm. CPU BIST and software BIST memory testing also have number of deficiencies. First, CPUs will not ordinarily have access to all memories. Providing such an interface increases the device cost. CPU functionality must be proved before memory testing can begin. The CPU BIST technique is slow and costly to develop because an expert device designer with thorough knowledge of the CPU must program the CPU to perform the testing. The CPU may not have back-to-back access capability to all memory-like logic. Wafer DMA or external BIST techniques are I/O speed limited and hence very slow. Dynamic memory failures like pre-charge and speed failures cannot be detected except at full device speed. The pBIST solution of this invention addresses all of these issues with considerably less logic than any competing techniques.

pBIST renders unnecessary the need to identify and deal with all memory failure issues and algorithms before tape-out. Using pBIST one can employ process qualifiers and processing on other devices with the advantage of making changes to testing techniques after tape-out when desired. Because the CPU-like logic is powerful, all useful comprehended algorithms are within the pBIST capabilities.

During activation of only a small portion of the chip, only the pBIST logic and the path to and from the memories, needs to be functional to validate the memories. This obviates the need for verifying in advance that the full CPU is functional. pBIST allows operation both from a program-



ming logic interface as well as the from the CPU interface. This permits maximum flexibility. pBIST has two logging features: (a) Failure-only logging technique; and (b) Stream-out capability. Both are invaluable for failure analysis.

FIG. 2 illustrates the pBIST architecture. pBIST has two main functional units. These are the pBIST controller **201** and the pBIST data-logger **202**. The pBIST controller **201** includes programmable logic that functions as a limited capability CPU and performs the memory stimulus. The pBIST data logger **202** compares the results from RAM datapath **203** with the expected results **214** from bus **212** and passes the comparison results to the external programming logic interface block **205** via bus **213**. At the tester interface **206**, the status of the memory testing as requested by the programmer is available. The external interface block **205** provides a CPU core interface bus **207** for configuration of the testing through the path provided by the CPU on the chip under test giving further leverage to the configuration task. A ROM interface **204** provides additional testing flexibility. RAM datapath block **203** provides the test interface to the multiple embedded RAMs under test and this includes:

1. Driving data **210** and instructions from pBIST controller **201**. A single bus **210** allows stimulus to be broadcast to all RAMs. A code signal **220** accompanying bus **210** signals to the target RAM that it is receiving data.

2. Output data on bus **211** (results of the test) is sent to pBIST data logger **202**. The code signal **220** also identifies the RAM providing the return data source.

The crucial requirement of the RAM datapath block **203** addressed by the pBIST approach is that its presence does not significantly degrade the memory performance in normal use. Reducing the required bus complexity of busses **210** and **211** using the coding scheme of signal **220** is a key to reducing complexity.

FIG. 3 illustrates the interconnection of the pBIST controller **301** and pBIST data logger **302**. The pBIST architecture includes program interface logic **305** and a microcode program control **313**. The program interface logic **305** includes configuration registers loaded through CPU interface bus **307**. Expensive, powerful test machines are rendered unnecessary for pBIST testing using a very low cost tester interface **306**. The microcode program control **313** stores all user-programming inputs entered via CPU interface bus **307**. The microcode program control **313** provides the memory access unit **314** with all new control and data information to drive the embedded RAM under test. This information includes control **308**, address **309**, select **310** and write data **311** for the up-coming clock cycle. The pBIST microcode program control **313** also drives functional processor units within the pBIST controller processor units **315**.

The data registers unit **320** receives outputs from three of the functional units within the pBIST controller processor units **315**: I-unit, A-unit, and C-unit. The I-unit, A-unit, C-unit are thus provided with two operands, (a) current operands from the microcode program control **313** and (b) next state operands, from the data register unit **320**. Similarly the memory access unit **314** is also provided with two operands, (a) current operands from the microcode program control **313** and (b) next state operands, from the data register unit **320**.

The program counters and branch logic **365** draws special emphasis to the role of the B-Unit in forming the instructions at bus **366**. Instructions **366** can proceed from a direct path from microcode program control **313** or from a branch route directed by the B-Unit.

The data register unit **320** holds all memory mapped register data, which includes:

Address Registers:

- (1) Constant Registers CA0 and CA1. These are 16 bits wide and may be modified only by initialization and external load operations. They cannot be incremented or decremented. CA0 and CA1 are assigned memory-mapped address **00A0** and **00A4** respectively in Table 5 below.

- (2) Variable Registers A0 and A1. These are 16 bits wide and they can be initialized, incremented or decremented and cleared. A0 and A1 are assigned memory-mapped address **0080** and **0084** respectively in Table 5 below.

- (3) Loop Count Registers include constants: CL0 and CL1. These are 16 bits wide and may be modified only by initialization and external load operations. They cannot be incremented or decremented. CL0 and CL1 are assigned memory-mapped address **00A8** and **00AC** respectively in Table 5 below.

- (4) Variable Registers L0 and L1. These are 16 bits wide and can be initialized, incremented or decremented and cleared. L0 and L1 are assigned memory-mapped address **0088** and **008C** respectively in Table 5 below.

Data Registers:

- (5) Constants D1, D0, and E1, E0, each of which is 32 bits wide and may be modified by initialization, C-unit and external load operations. They cannot be incremented or decremented. D0 and D1 are assigned memory-mapped address **0090** in Table 5 below. E0 and E1 are assigned memory-mapped address **0094** in Table 5 below.

- (6) The increment registers including constants IO and I1. These registers are 16 bits wide and may be modified only by initialization and external load operations. They cannot be incremented or decremented. IO and I1 are assigned memory-mapped addresses **00B0** and **00B4** respectively in Table 5 below.

The memory access unit **314** passes to the pBIST data logger **302** the following:

- (a) expected results information (write data **311**), and
- (b) address information (address **309**) to the pBIST data logger input registers pipeline **318**. Actual results, read data **317** directly from the RAM under test also passes to data logger pipeline **318** for comparison in mask and compare unit **322**. Compare results may be masked in the mask and compare unit **322** using mask **324** before being passed to the pBIST data logger output unit registers **326**. Address information is tracked in the data logger via signal **329**. Mask features include: (a) data width, (b) column fail, and (c) time stamp. Data Logger Outputs include: Done, Fail, and Run status outputs **330** and Logout **333**. The CPU IF **307** interfaces with the memory mapped registers **341**. The data logger output unit **326** includes the status registers **338**, status output logic **339**, the memory mapped registers **341**, and serial logout via serial logout **340**. Further description of the pBIST data logger is given below in FIGS. 7, 8, and 9.

FIG. 4 illustrates a lower level diagram of the pBIST controller **301** hardware of FIG. 3. The pBIST controller includes a microcode program control unit **413**. The microcode program control unit **413** stores all user-programming inputs entered into the programming logic interface unit **470** via paths: CPU IF **407**; ROM IF **404**; and tester IF **406**.

Status information from each processor unit is also passed to the microcode program control unit **413** via status input **330** from the data logger **302** of FIG. 3. The CPU IF **407** provides all data information and all control and address information to drive the embedded RAM under test via its path **468** to the instruction register file **460** and to the data



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registers 420 via path 469. The data registers in turn feed the main data bus 450. Main data bus information includes control and data output signals: control 308; address 309; select 310; and write data 311 all of which are current for the up-coming clock cycle. The pBIST instruction register file 460 drives, via bus 440, the functional processor units within the pBIST including: M-unit 451, I-unit 452, A-unit 453, C-unit 454, B-unit 465, zero detect unit 455, and address scrambler unit 461. The data registers 420 receives the destination addresses 455, 456, and 457 from the I-unit 452, the A-unit 453, and the C-unit 454 respectively. These destination addresses are passed from the data registers 420 to the main bus 450. Four functional units within the pBIST controller processor units: I-unit, A-unit, C-unit, and B-unit are thus provided with operand addresses from which the subsequent address and control inputs are computed in the memory access unit 414.

The Branch-unit 465 performs tests on source addresses and generates instructions that are passed to the instruction bus 440. The branch unit 465 performs the comparisons and tests using program counter A 443 and program counter B 444 states as additional inputs. Opcode MUX 464 selects and instruction register 466 stores the results of the comparisons and supplies instructions to the instruction bus 440.

The data registers 420 forms a holding register stage for each of the parameters distributed by the main bus. These are: A0, A1, L0, L1, D0, D1, I0, I1, E0, and E1 and they are described in the list of memory-mapped registers in Table 5.

pBIST logic supports a compact set of instructions that allow a user to perform memory testing. The primary assumption is that pBIST can be completely initialized to any state and then enabled to execute the required limited set of instructions. The preferred pBIST design can execute as many as 32 separate instructions. This is more than sufficient for most of the testing found necessary in designs in process or contemplated. The pBIST logic can be configured in two steps:

1. Set maximum hardware requirements through specified parameter in a software RTL. Parameters including, the number of entries and the maximum pipeline latency, for example, are defined below.

2. Programming RAM(s) specific requirements and memory testing algorithms. The current implementations (memBIST from Logic Vision and mBIST from Mentor) have the limitation that they must be programmed before tape-out. This assumes that the memory testing issues are all identified and bounded into a set of vectors before tape-out, which is almost always not true for process drivers. Most algorithms are based on the previous technology used in earlier devices. Designers often do not have a clear understanding of the current technology issues. As a result, the engineering evaluation effort often attempts to proceed using a CPU BIST, which of itself has a number of limitations. Back-to-back accesses are often impossible due to architectural limitations. As another example, if the L2 memory receives a burst inside a bank in current methodology pBIST provides a fast and thorough testing platform allowing this feature to be exercised.

pBIST supports two instruction types classified as general and load. The instruction width is 32-bits. The valid bit in the A-, I-, and C-, units can be combined with operation bits to expand the opcode if this provides the user additional features. The opcode formats for the M-, I-, A-, C-, and B-units are illustrated in FIG. 5 (501-505) general instructions. The second portion of FIG. 5 labeled 506-508 illustrates load-type instructions.

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pBIST Utilizes the Following Processor Units:

The M-unit (Main Unit) handles the RAM read/write, program flow and load controls. It uses 7 bits of the pBIST opcode (see 501 and 506 in FIG. 5).

The I-unit (Increment/Decrement Unit) performs addition/subtraction on addresses A0, A1, L0 and L1 with an increment or decrement of 1. The I-unit uses a 4-bit opcode (see 502 of FIG. 5 and Table 1).

TABLE 1

I-Unit Instructions	Valid	INCR/DECR	Source	
Operation Bits	24	23	22	21
INCREMENT L0	1	0	0	0
INCREMENT L1	1	0	0	1
INCREMENT A0	1	0	1	0
INCREMENT A1	1	0	1	1
DECREMENT L0	1	1	0	0
DECREMENT L1	1	1	0	1
DECREMENT A0	1	1	1	0
DECREMENT A1	1	1	1	1
NOP	0	X	X	X

The A-unit (Addition/Subtraction Unit) performs 16-bit addition and/or subtraction on addresses A0, A1, L0, L1 with I0 and I1 increment sizes. The A-unit employs a 5-bit opcode (see 503 of FIG. 5 and Table 2).

TABLE 2

A-Unit Instructions	Valid	ADD/SUB	SRC 1	SRC 2
Operation Bits	20	19	18	17
ADD: A0 + L0	1	0	0	0
ADD: A1 + L0	1	0	0	1
ADD: I0 + L1	1	0	1	0
ADD: I1 + L1	1	0	1	1
SUB: A0 - L0	1	1	0	0
SUB: A1 - L0	1	1	0	1
SUB: I0 - L1	1	1	1	0
SUB: I1 - L1	1	1	1	1
NOP	0	X	X	X

The C-unit (Combination Unit) performs shift/rotate/logic operation on addresses A0, A1, D1:D0, and constants E1:E0. The C-unit can support 16 or 32 bit operands and uses an 8-bit opcode (see 504 of FIG. 5 and Table 3).

TABLE 3

C-Unit Instructions				
Operation Bits	14	13	12	11
NOP	0	0	0	0
A = A AND B	0	0	0	1
A = A OR B	0	0	1	0
A = A XOR B	0	0	1	1
A = NOT A	0	1	0	0
A = NOT (A AND B)	0	1	0	1
A = NOT (A OR B)	0	1	1	0
A = NOT (A XOR B)	0	1	1	1
A = SHL A	1	0	0	0
A = ROTL A	1	0	0	1
A = SHRU A	1	0	1	0
A = ROTR A	1	0	1	1
A = NOT B	1	1	0	0
A = 0	1	1	0	1
A = 1	1	1	1	0
A = GRAY B	1	1	1	1

The B-unit (Branch Unit) performs zero detection and branch decision logic. It uses an 8-bit opcode (see 505 and 508 of FIG. 5 and Table 4).



TABLE 4

B-Unit Instructions				
Operation Bits	8	7	6	5:0
BNZ L0	0	0	0	ADDRESS
BNZ L1	0	0	1	ADDRESS
BNZ A0	0	1	0	ADDRESS
BNZ A1	0	1	1	ADDRESS
BNZ FAIL	1	0	0	ADDRESS
BNZ REP	1	0	1	ADDRESS

FIG. 6 illustrates M unit instructions in greater detail. For clarity these M unit instructions may be broken down into the following major types.

(1) READ—This instruction reads the memory under test. It has two major variations and other possibly useful ones are available. The return data may be compared with an expected value. If a mismatch occurs the pBIST controller may stop or log and continue based on the setup. Also this option can be disabled. Its variations are: Read **603**, Read without compare, and Sub-Width Reads **601** and **602** with or without compare.

(2) WRITE—This instruction writes to the memory. The return data may or may not be compared. Variations are: (a) Write, (b) Write with return data compared, (c) write-through with return data compared and (d) write modified read with return data compared (see **603** of FIG. 6).

(3) NOP—This instruction does nothing as its name suggests. It is used to perform internal activities internal to the pBIST controller or to add a delay slot (see **610** of FIG. 6).

(4) LOAD—The LOAD instructions are of two types: (a) move shadow (MVS) and move immediate (MVI) opcodes used are illustrated in FIG. 6).

(5) Move Shadow (MVS) instruction performs register loading inside the pBIST. All registers enabled get loaded with their shadow value. The MVS instruction operand has three options (see **607** of FIG. 6):

- 1) Load all registers with shadow
- 2) Load only enabled registers with shadow
- 3) Load none of the registers

(6) MVI (Move Immediate) instruction acts as a Load Immediate which loads the data to the byte pointed to by the address See **608** of FIG. 6).

(7) HALT—On this instruction the execution stops and the CPU is not modified. Data logging stops after a delay of N clock cycles where N is the number of pipeline stages in the pBIST controller (see **611** of FIG. 6).

A summary of processing in other microcontroller processing units follows.

The I-unit increments or decrements either L0, L1, A0 or A1 according to the code **502** in FIG. 5. Bit **20** is a valid bit allowing enabling or disabling of the increment operation.

The A-unit adds or subtracts combinations of sources from registers L0, L1, A0 or A1 according to the code **503** in FIG. 5. Bit **20** is a valid bit allowing enabling or disabling of the addition/subtraction operation.

The C-unit performs shift/rotate/logic operation on A0, A1, D1:D0, and E1:E0 according to the code **504** of FIG. 5. The C-unit can support 16 or 32 bit operands.

The B-unit performs branching as follows. The program counter (PC) takes the address pointed to by the instruction. If the valid bit is active, then the LOOP count [A0, A1, L0, or L1] if zero will transfer the program counter content to address+1. If the LOOP count is not zero the branch is taken.

### Address Scrambling

Address scrambling registers SCR0 and SCR1 are a feature of pBIST that is available through the M-unit and is illustrated by M-unit address scrambler **461** of FIG. 4.

Incorrect address connections detected after the device has been submitted for tape-out do not allow the correct operation of the algorithms developed. Address scrambling is a technique by which the programmer can correct the address problem. The address scrambler provides a one-to-one connection for all 16-bits of A0 and A1 to the RAMs. The default value of the SCR register at reset is: SCR[63:0] = hexadecimal FEDCBA9876543210. By modifying these values any address mapping may be achieved. As an example consider the case wherein the address values 8 and 7 are reversed. The programmer needs merely to modify the SCR to become: SCR[63:0] = hexadecimal FEDCBA9786543210. With this change the memory map can be properly accessed as the algorithm intended. Address scrambling has two dedicated memory-mapped registers listed in Table 5 under addresses **00D0** and **00D4**.

### Configuration Registers

There are five configuration registers in pBIST included in programming logic interface configuration registers **470** of FIG. 4. These registers and the configuration options they select are:

(1) Clock Multiplexer Select (CMS): selects between (a) test clock, (b) base maximum frequency CPU clock, and clock domains (c) half-frequency clock, clock2, and (d) one fourth frequency clock, clock4. CMS is listed with memory-mapped registers under address **00C8** in Table 5

(2) Sense Margin Select (SMS): selects between (a) slow functional, (b) test slow, (c) fast functional, and (d) test fast.

(3) Pipeline Latency Select (PLS): selects between 0 through 15 cycle latency for comparison of data from RAM interface with expected data. The data logger employs optional pipeline register stages that may be configured for this range of latency.

(4) RAM Latency Select: pBIST supports four RAM latency selections: 0, 1, 2, or 3 clock cycles. The pBIST controller sends one access for every N cycles. This is necessary for RAMs, which are clocked at a higher frequency to reduce latency. Pipeline latency is the sum of the datapath latency plus the RAM latency. The programmer must assure that the expected data arrives after the programmed delay. This register is part of the RAMT register which includes (1) RGS; (2) RDS; (3) Data Width; (4) Pipe Latency; and (5) RAM Data.

(5) Chip Select CSR: pBIST implements a chip select for up to 32 RAMs. When a READ or WRITE command is executed, the corresponding chip select is driven active and enables the selected RAM. Chip select (CSR) is listed with memory-mapped registers under address **00D8** in Table 5

(6) Program Control Register STR[4:0]: this register is five bits wide as listed under address **00CC** with memory-mapped registers in Table 5. Each bit is an active high enable for program control features.

STR(0) pBIST Start. Begins testing after pBIST has been enabled.

STR(0) Resume Testing. STR(1) going high resumes execution after an error is detected. When pBIST detects an error, it will log a fail signature. Using the configuration bus the programmer reads the status register and can resume operation. If only one error is detected, pBIST continues execution and will ignore the resume code occurrence. If a second error is detected, pBIST will stall. The second failure will be



loaded to the failure signature registers. These fail signature registers include FSRF, FSRC, FSRA, and FSRD included in memory-mapped register list in Table 5 under addresses 00F0, 00f4, 00f8, and 00FC respectively. Assume after a resume operation that a fail is encountered and a second interrupt is issued. When a configuration bus read of the second failure is completed, the pBIST will continue operation.

STR(2) Stop Testing. Stop operation bit acts to stop execution of the memory testing for any assigned reason.

STR(3) Step Testing. In step test mode the test engineer may execute one instruction and stop for a time to review the results and then proceed one test at a time if desired.

STR(4) Enables pBIST. Enable mode selects the pBIST controller if multiple controllers are supported. Cycle begins by resetting the CPU and starting execution from the initialized state.

(7) Data Width Register DWR[7:0] is part of RAMT register: This register is used to decide the data width to the RAMs. The value DWR represents the data width of the RAM. The decoded bits that are enabled will be compared for return data with the constant data registers selected. RAMT is listed in Table 5 of the memory-mapped registers under address 00C0.

(8) Column Mask Register [31:0] (Internal, not a memory mapped register): In the column mask mode, this register stores the multiple bit fails within a column and masks this column from the next column fail detect. This allows detection of a failed column but excludes multiple failures within a given column from triggering unnecessary failures.

(9) Time Stamp and Time Stamp Fail Mask Registers [31:0] (Internal, not memory mapped): These registers are enabled in the time stamp mask mode when it is useful to skip all instructions until the previous failure and then enable failure logging. This preserves the algorithms intended operation.

(10) Data Logger Control Register [7:0] DLR: The data logger is controlled from this 8-bit register as listed under address 00C4 with memory-mapped registers in Table 5. DLR(7:3) are active high enables for data logger features. The remaining bits DLR(2:0) are reserved for added further functions.

DLR(7) activates time stamping;  
DLR(6) activates column fail masking;  
DLR(5) activates stream mode;  
DLR(4) activates configuration inputs;  
DLR(3) activates TCK gated mode.  
DLR(2) reserved.  
DLR(1) reserved.  
DLR(0) reserved.

(11) RAM Group Select [15:8] (RGS, part of RAMT register): In order to support more than 32 RAMs this RAM group select register has been provided. This extends the total number of RAMs that can be tested from 32 to 8192 RAMs of 32 bits or less. RAMs with data width larger than 32 are tested as more than one RAM and data logged separately.

(12) Return Data Register RDS 31:16, is part of RAMT register.

#### Status Outputs and Fail Status Registers

There are three status outputs from the pBIST output unit 326 that are included in status 330. These are (1) Done and (2) Run signals generated in micro-code program control 313, and (3) fail, generated in the output unit 326 from the

flag (FSRF) signal in the status register 338. Fail Status Registers 338 of the pBIST output unit 326 includes four registers: (1) FSRF (fail flag); (2) FSRC (fail count); (3) FSRA (fail address) and (4) FSRD (fail data).

(1) Fail Flag Register FSRF[0]. This one bit register is cleared at reset and when start or pBIST\_enable is activated. This 1-bit register represents the failure status of the current execution phase at that point. It is driven high the moment the data logger makes a negative compare. It is also connected to the pBIST\_fail output bit of the pBIST controller. Memory-Mapped address is 00F0 in Table 5.

(2) Fail Count Register FSRC [7:0]. This register is cleared at reset and when start or pBIST\_enable is activated. This 8-bit register represents the failure count of the current execution phase at that point.

(3) Fail Address Register FSRA [15:0]: This register stores the event of a negative compare on address when the finite state machine signal FSR is logical 1. Memory-Mapped address is 00F8 in Table 5.

(4) Fail Data Register FSRD [31:0]: This logout register stores the compare status by data width. It is valid only when Fail Status Register is a logical 1. The register is cleared during reset or when start or pBIST\_enable is activated. When a failure is detected, the pBIST controller stops immediately and, based on the mode selected, either scans the failure out, broadcasts it to the I/O pins or waits for the user to read it out before continuing. If the user mode is selected, then the Restart register must be toggled to continue. The Compare Status register and Address register are valid only if data logging is enabled. Memory-Mapped address of FSRD is 00FC in Table 5.

#### Memory Mapped Registers

All pBIST registers of interest to the user are memory mapped to be accessible from Tester IF 406 or CPU IF 407. The CPU interface is for parallel accesses and usually for speed. Scan based initialization is also available. The memory mapping of all the pBIST internal registers is described below. A full listing of memory mapped registers, addresses and contents is illustrated in Table 5.

TABLE 5

Address (hex)	Register	Description	Bits			
			31:24	23:16	15:8	7:0
0000	RF0	Register	RF0	RF0	RF0	RF0
003C	RF15	File	RF15	RF15	RF15	RF15
004C	RF16	—	RF16	RF16	RF16	RF16
007C	RF31	Expansion	RF31	RF31	RF31	RF31
0080	A0	Address			A0	A0
0084	A1	Address			A1	A1
0088	L0	Variable			L0	L0
008C	L1	Variable			L1	L1
Shadow Registers						
0090	D1:D0	Constant	D1	D1	D0	D0
0094	E1:E0	Constant	E1	E1	E0	E0
00A0	CA0	Constant			CA0	CA0
00A4	CA1	Constant			CA1	CA1
00A8	CL0	Loop Count			CL0	CL0
00AC	CL1	Loop Count			CL1	CL1
00B0	I0	Increment			I0	I0
00B4	I1	Increment			I1	I1
00C0	RAMT	RAM Info	RDS 31:24	RDS 23:16	RGS 15:8	DWR 7:0
00C4	DLRT	Data Logger Mode				DLRT 7:0
00C8	CMS	Clock Mux Select				CMS 1:0
00CC	STR	Program Control				STR 4:0



TABLE 5-continued

Address (hex)	Register	Description	Bits 31:24	Bits 23:16	Bits 15:8	Bits 7:0
00D0	SCR0	Address	SCR0	SCR0	SCR0	SCR0
00D4	SCR1	Scramble	SCR1	SCR1	SCR1	SCR1
00D8	CSR	Chip Select	CSR	CSR	CSR	CSR
<u>Fail Status</u>						
00F0	FSRF	Fail Flag				Flag bit0
00F4	FSRC	Fail Count				Count 7:0
00F8	FSRA	Fail Addr			FSRA	FSRA
00FC	FSRD	Fail Data	FSRD	FSRD	FSRD	FSRD

### Configuration Bus Interface

In the configuration mode, the programmer has complete flexibility on how to test and debug the pBIST operations. With the interrupt handshake between the CPU and pBIST controller, the programmer can test any memory in the chip and does not have to be concerned with any particular RAM. For example, in a current design using CPU BIST when testing the L1I RAM or TAG, the programmer needs to be concerned as to what memory is being tested and how to run the program without the memory testing interfering with the CPU operation. By contrast using pBIST mode the programmer can run the code, setup the pBIST controller and go into IDLE and when the interrupt occurs, the programmer codes the interrupt handler such that no bad code is executed.

The operations performed are as follows:

1. Setup the pBIST controller.
2. Before start all functional memories/register files that will be tested by pBIST must be set in bypass mode. Any memory content modified by pBIST for testing purposes should not impact normal pBIST testing sequences.
3. Start pBIST.
4. CPU goes into IDLE mode.
5. pBIST Testing in progress. pBIST interrupts CPU on failure.
6. CPU Interrupt routine is initiated with two possible options.
  - A. Check failure status, make code modifications to work around failure and restart pBIST.
  - B. Interrupt routine is non-cacheable or L1I is turned off.

### Programming Logic Interface

The programming logic interface (PLI), 470 of FIG. 4, is necessary to avoid RAM testing dependence on CPU functionality. Using the PLI, pBIST initialization and operation is controlled from outside the chip. Only the pBIST logic functionality is necessary for performing RAM testing.

The steps involved PLI interface testing are:

1. Enable pBIST test mode.
2. Initialize pBIST controller.
3. Load program.
4. Start testing
5. pBIST controller starts RAM testing.
6. Failure will log status and scan it out at TCK frequency
7. Testing continues until multiple failure and then will run lock step with data logging and scan-out.
8. Program completion triggers the done signal and PASS/FAIL signature is output.

### Micro Architecture (Repairable RAMS)

Repairable RAMS require multiple fail data logging for row/column error correction. In this mode there are a number of options. These tests can be run via CPU IF or PLI

interfaces. In the configuration bus interface CPU interrupts or time-out modes are supported. The programmer starts the pBIST controller. The pBIST controller runs until it captures a failure. The CPU can start the testing on pBIST and go into IDLE mode. The pBIST controller activates the interrupt both on failures and on end of test. When interrupted, the CPU can then read the fail status registers and determine the next step. The pBIST controller is stalled when a second failure happens. The CPU writes a logical 1 to the resume bit to continue to the next failure.

FIG. 7 illustrates the structure of a basic data logger function. The pBIST data logger includes three parallel pipelines passing address and data information in-step to preserve latency timing. Data stimulus 701 for the RAM under test is sent to two parallel registers. Register 703 is the data path to the RAM under test and data register file A 705 preserves a copy for test comparison. Address enters at address inputs 707 and enters address register file B 709. As read data from the RAM under test returns at 317 it is stored in read data register 706. At the same clock time, registers 706, 708, and 711 are clocked to receive actual data 317, expected data 718 and corresponding address value 719. Data 317 and 718 as stored in registers 706 and 708 respectively are submitted to mask and compare unit 712. Mask inputs are provided by mask 714 and mask and compare unit output 715 is sent to pBIST data logger output unit 726 for processing into outputs 330 and 333 as described in FIG. 3. Corresponding address information 716 is passed from address output stage 713 to data logger output unit registers to be matched to compare output 715 for presentation of output results. Memory mapped registers 341 hold all fail status information including Fail, Fail Count, Fail Data, and Fail Address as stored in the fail status registers 338. This information is accessible at the CPU IF 307. An interrupt is also sent to the CPU via CPU IF 307. Serial logout 340 allows passage of the same information to the user at logout 333. Status outputs 330 from block 339 include Done and Run which are derived from the program control 313 at input 337 and the Fail output derived from mask and compare output 715.

pBIST provides additional RAM datapath interface options with improved throughput. Two possible designs include the shared data logger and the distributed data logger. The shared data logger structure illustrated in FIG. 8 has a relatively simple implementation and requires minimal additional hardware. The shared data logger uses the data logger pipeline 318 described in FIG. 3 and FIG. 7 and multiple RAMs connected and driven from busses 308, 309, 310 and 311. In FIG. 8 the RAM return data from all RAMS 800 through 899 passes to multiplexer 820 via paths 810, 811, 888, 889 for return to the pBIST data logger mask and compare unit 812 via 830. Compare results may be masked in the mask and compare unit 812 using mask 814 before being passed to the pBIST data logger output unit 826. Mask features include: (a) data width, (b) column fail, and (c) time stamp. Expected Data 828 and Address 816 are supplied by the data logger pipeline 318. Data Logger Outputs include: Done, Fail, and Run status outputs 330 and Logout 333. The CPU IF 307 interfaces with the memory mapped registers 341. The data logger output unit 326 includes the fail status registers 338, status output logic 339, the memory mapped registers 341, and serial logout via serial logout 340.

The advantage of the shared data logger is that the designer needs merely to route and multiplex down the RAM return data and bring it back to the pBIST. The pBIST controller (710 of FIG. 7) takes care of data logging and stalling on fails.



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FIG. 9 illustrates the distributed data logger in which data logging is done at the individual RAM locations. The distributed data logger also uses the data logger pipeline 318 described in FIG. 3 and FIG. 7 and multiple RAMs connected and driven from busses 308, 309, 310 and 311 as well as expected data from bus 317. The RAMs are illustrated as 900, 901, 998, and 999. Compare blocks 910, 911, 918 and 919 perform the same mask and compare described earlier with masking coming from mask 914. The logic for compare of the return data 930, 931, 938, 939 with the expected data 989 is placed at the RAM output and two signals are retrieved from the individual RAMs. These are Pass/Fail 926 and logout 917. Address 916 is supplied by the data logger pipeline 318. Data Logger Outputs include: Done, Fail, and Run status outputs 330 and Logout 333. The CPU IF 307 interfaces with the memory mapped registers 341. The data logger output unit 326 includes the fail status registers 338, status output logic 339, the memory mapped registers 341, and serial logout via serial logout 340. The distributed data logger option allows parallel testing of RAMs but requires additional replicated logic at the RAMs.

## Time Stamping Mask Mode

In the absence of a time stamping mask, failures that occur cause the pBIST controller to cease testing, process the failure, and continue testing from the point where the testing had ceased. Then when the testing operation is continued, back-to-back testing has been interrupted and hidden failures may result. Time Stamp Mask Mode operation remedies this difficulty. Using the time stamp fail mask pBIST saves the time stamp of the last failure and generates a TS fail mask.

FIG. 10 illustrates the pBIST time stamp mask mode operation. Assume the user initiates the start of testing in the time stamp mask mode. The pBIST controller begins at start block 1000 and because no failures have yet occurred, it bypasses error checking at the TS fail mask block 1002 where only an existing TS fail mask record would cause ignoring of previously processed fails. The pBIST controller then executes an instruction and captures and compares return data in block 1003. If test 1004 detects a fail (a Y result) the path 1020 into a return loop 1031 is taken. Loop 1031 can be referred to as the process new fails loop. If test 1004 results in a pass (a N result), another test is performed in block 1008 to determine whether end of testing has occurred. If end of testing has not been reached, the path 1009 back to the start of loop 1033 is taken. Loop 1033 can be referred to as the search for new fails loop. If end of testing has been reached in test 1008 path 1019 is taken to a done state.

The steps in return loop 1031 are (a) to capture the fail signature 1005, (b) process the fail information 1006 and (c) set TS fail mask as the time of failure in block 1007. Fail information is processed by: (1) logging a fail at output 331 of the data logger (FIG. 7) and (2) passing the fail signature through data logout 333 of FIG. 7. The fail signature is stored in memory mapped registers within the pBIST data logger 716 and may be passed to the CPU IF as an alternative means of outputting fail signature data. Once this is accomplished and the time stamp recording of the TS fail mask time of block 1007 has been completed, testing returns to the loop 1031 return point 1001 where the attempt to capture a fail mask in block 1002 is re-initiated. The updated TS fail mask information from block 1007 is then used to perform later occurring tests in block 1002.

A positive result in block 1002 results in an exit to loop 1032 where instructions are executed but return data is

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ignored in block 1010. Loop 1032 can be referred to as the ignore previous fails loop. Query on whether TS fail mask time has been reached is performed block 1011. A positive result causes entry via 1012 into loop 1033 to search for new fails; a negative result in block 1011 continues loop 1032 via path 1013 and previous fails are ignored until TS fail mask time is reached in test 1011.

On entering loop 1033 the next instruction is executed and return data is compared to expected results in block 1003. A fail in block 1004 causes a return to loop 1031. No fail in block 1004 leads to end of testing query in block 1008. If the testing is not ended path 1009 is taken with the continuing of loop 1033 and the search for new fails. Data logging is enabled and testing continues. At the end of the test 1019 the result is that all failures were detected only once and the expected testing operation of the algorithm is achieved in the done state.

pBIST programming for specific testing is based on knowledge of the structure and operation of the RAM to be tested. The row-column structure of a typical RAM and the addressing, write operations, and read operations collectively give the task of testing clear initial direction. Test sequences that generate interactions between cells or rows or columns can be used to verify the robustness of the design or the topology of the RAM layout. Test sequences that force stores bits in the RAM alternately from '1' to '0' and back to '1' exercise worst cases involving sense amplifier operation are another common means used to identify weakness in the design or layout.

An extremely large effort to address these test cases has resulted in sophisticated algorithms being developed for almost any RAM design weaknesses that have been identified in the past or expected as new designs place pressure on the parameters of the fabrication process. The capability to develop these algorithms is clearly useful to complete testing of new designs in wafer form using pBIST. Once the device has been fabricated, pBIST testing can be applied to exercising even the most extreme states that a design can encounter. If any weaknesses are uncovered, then the programmability features of pBIST allow for tracking RAM failures in even unrealistically extreme operating conditions.

The full width testing sequence illustrates a simple example of pBIST programming. The code and a line-by-line description of the code is illustrated below.

## Full Width Testing Algorithm

* INIT	Involves Two Steps:		
* Load CL0 with M-1; Load CA0 with hex '0'			
* Load D1:D0 with hex:0.			
* Initialize all RAM bits to 0 by looping from 0 to (N-1)			
Address	Mnemonics		
LINE NUMBER			
1100	.M MVS	A0, L0	
1101 LOOP1:	.M WRITE	A0, D1: D0	
1102	.A ADD	A0, I0	
1103	.I DEC	L0	
1104	.B BNZ	L0	LOOP1
* LOAD	Re-initialize Address and Loop Count		
*	for "Read-Write-Read" Loop		
1105	.M MVS	A0, L0	
* TEST			
* Read zeros, Write ones, Read ones on address 0 to N-1			
1106 LOOP2:	.M READ	A0, D1:D0	
1107	.M WRITE	A0, ~D1:D0	
1108	.M READ	A0, ~D1:D0	
1109	.A ADD	A0, I0	
1110	.I DEC	L0	



-continued

Full Width Testing Algorithm			
1111	1.B BNZ	L0	LOOP2
* HALT			
* Test Complete			
1113	1.M HALT		

Comments by Line Number:  
1100: Move Shadow MVS moves CA0 to A0 and CL0 to L0  
1101: Start of LOOP1:  
    WRITE M-instruction writes address A0 into concat-  
        enated registers D1:D0.  
    Three parallel operations in lines 1102, 1103, and 1104  
        follow.  
1102: ADD A-operation adds I0 to A0 and places result into  
        register A0.  
1103: DEC I-operation decrements register L0.  
1104: Branch B-operation branches to LOOP1 if L0 has  
        been decremented to zero in line 1103.  
1105: Move Shadow MVS moves CA0 to A0 and CL0 to L0  
1106: READ M-instruction reads from address A0 the  
        concatenated registers D1:D0.  
1107: WRITE M-instruction writes to address A0 the  
        inverted bits ~(D1:D0); tilde indicates all bits inverted.  
1108: READ M-instruction reads from address A0 the  
        previously written data ~(D1:D0).  
1109: ADD A-operation adds I0 to A0 and places result into  
        register A0.  
1110: DEC I-instruction decrements L0 register.  
1111: Branch B-operation branches to LOOP2 if L0 has been  
        decremented to zero in line 1110.  
1112: HALT Ends testing.  
What is claimed is:  
1. A data processor system comprising:  
at least one read/write memory;  
a programmable memory test controller operable to per-  
form a sequence of memory test operations according  
to an alterable set of instructions,  
said programmable memory test controller including a  
plurality of special functional units of differing types  
each controlled by a corresponding part of said instruc-  
tions; and  
a results logger operable to compare data read from said  
at least one read/write memory with expected results.  
2. The data processor system of claim 1, further compris-  
ing:  
a set of data registers including at least one data register  
operable to store data to be written to said at least one  
read/write memory; and  
wherein said plural special functional units include an  
arithmetic unit operable to selectively add or subtract  
data stored in said data registers.

3. A data processor system comprising:  
a plurality of read/write memories;  
a programmable memory test controller operable to per-  
form a sequence of memory test operations according  
to an alterable set of instructions;  
a results logger operable to compare data read from said  
at least one read/write memory with expected results,  
said results logger including  
a multiplexer having a plurality of inputs, each input  
receives read data from a corresponding one of said  
plurality of read/write memories, said  
multiplexer further having a control input and an output,  
said multiplexer coupled to a selected one of said  
plurality of inputs to said output dependent upon said  
control signal, and  
a comparator connected to said output of said multiplexer  
operable to compare data from said read/write memory  
selected by said multiplexer with corresponding  
expected results.  
4. A data processor system comprising:  
a plurality of read/write memories; a programmable  
memory test controller operable to perform a sequence  
of memory test operations according to an alterable set  
of instructions; and  
a results logger operable to compare data read from said  
at least one read/write memory with expected results,  
said results logger including a time stamp register oper-  
able to store a time stamp upon detection of a mismatch  
of said data read from said at least one read/write  
memory with said expected results, and  
said results logger operable in a time stamp mask mode to  
indicate a match when an elapsed time of a current test  
is less than or equal to said time stamp stored in said  
time stamp register, whereby said data processing sys-  
tem is operable to re-execute a sequence of memory  
test operations from a start and ignore previously  
detected mismatches.  
5. A data processor system comprising: at least one  
read/write memory;  
a programmable memory test controller operable to per-  
form a sequence of memory test operations according  
to an alternate set of instructions; and  
a result logger operable to compare data read from said at  
least one read/write memory with expected results, said  
results logger operable to stop said sequence of  
memory test operations upon detection of a mismatch  
between data read from said at least one read/write  
memory and said expected results, and  
resume said sequence of memory test operations upon  
receipt of a resume command.

\* \* \* \* \*